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Contributed paper

Ex situ and *in situ* methods of inspecting and optimizing adaptive bimorph mirrors

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At the Diamond Light Source, adaptive bimorph mirrors are extensively used to focus synchrotron light. Piezo crystals embedded in each bimorph mirror expand or contract in response to applied voltages, enabling the curvature of the reflecting surface to adapt to the required form. However, high-grade metrology tools are needed to determine the optimal voltages. The Diamond Optics & Metrology group have implemented *in situ* (on the beamlines) and *ex situ* (in a metrology lab) methods of characterizing optical surfaces. For *ex situ* tests, a slope-measuring profiler (the Diamond-NOM (Nanometre Optical Metrology)) is employed. *In situ*, X-ray pencil beam scans, performed using an X-ray sensitive camera and software designed in-house, are used to correct optical slope errors. *Ex situ* and *in situ* data are shown to be in good agreement. Examples of *in situ* improvements in the focusing quality and deliberate defocusing are shown. The methods developed are also applicable to many other forms of adaptive optics.

1. Introduction

Bimorph mirrors (Susini *et al.*, 1995) are widely used at many synchrotron facilities because of their adaptability. However, effective and efficient strategies are required to optimize each bimorph's many degrees of freedom. A metrology cleanroom lab has been established for *ex situ* characterization of Diamond's optics. The suite of instruments includes a slope-measuring profiler, the Diamond-NOM, to record slope/figure errors. After installing the optics on the beamlines, *in situ* techniques, including X-ray 'pencil beam' scans, are used to further optimize the alignment and focusing properties of the bimorph mirrors.

2. Diamond-NOM

The Diamond-NOM (Alcock *et al.*, 2010) is a non-contact, slope-measuring profiler, capable of measuring the surface topography of large mirrors with sub-nanometre resolution and repeatability (figure 1). A narrow beam (~3 mm) of light from an electronic autocollimator (Elcomat 3000, Moeller-Wedel) is directed onto the test surface and records the local deflection angle. Computer-controlled

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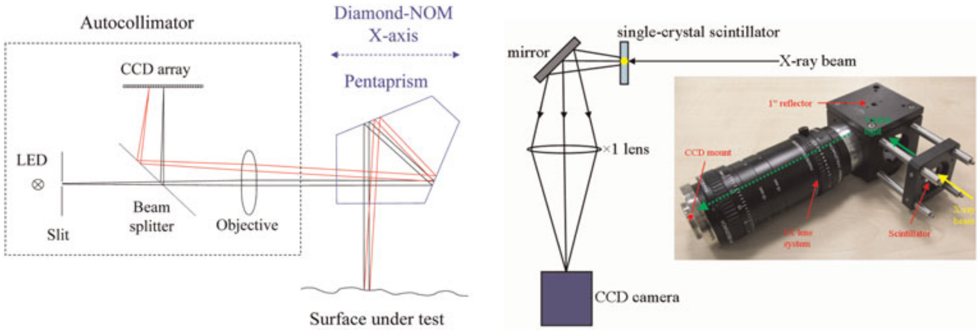

FIGURE 1. Schematic of the Diamond-NOM (left) and the X-ray camera (right).

air-bearing stages and a pentaprism scan the autocollimator beam along the optic and determine its slope profile. The Diamond-NOM can accommodate optics up to 1700 mm long × 1000 mm wide × 700 mm high. The r.m.s. difference between two similar scans (repeatability) is <100 nrad, and the uncertainty falls to <50 nrad r.m.s. if several scans are averaged.

3. *In situ* apparatus

An X-ray camera, shown in figure 1, was assembled using off-the-shelf components. A Ce:YAG scintillator illuminated by X-rays produces visible light from which the lens creates an image on the CCD (charge-coupled device) camera. The 90 % integrated line spread function is 4.65 μm (50-μm-thick scintillator) or 6.35 μm (100-μm-thick scintillator). Pencil beam scans were executed and processed through generic data acquisition. Diamond's Data Acquisition and Scientific Computing group wrote a Jython script to calculate the centroid position of a beam on the X-ray camera and another to derive the voltage corrections, thus automating the entire voltage optimization procedure. Each mirror was scanned with the pencil beam covering 3–5 mm of the surface at a time, first with all voltages in their initial state, then with each voltage raised in turn by a fixed amount (usually 50 or 100 V). The reflected beam positions yield an 'interaction matrix' that is inverted to focus the beam (Hignette *et al.*, 1997).

4. Results and conclusions

Although the voltages were set slightly differently (to bend the mirrors to circular or elliptical shapes in the *ex situ* and *in situ* tests, respectively), similarities are clearly visible in the *in situ* and *ex situ* slope error plots shown in figure 2. The sharp jumps in the slope error graphs were found to be located at the interfaces between the electrodes. They are part of the residual slope errors left after the electrode voltages are optimized. A representative example of the improvement in the size and shape of the focal beam spot is shown in figure 3. The focused beam FWHM size was 88 × 60 μm. Deliberate defocusing to a 167 × 84 μm FWHM (full width at half-maximum) size was also achieved. The unidirectional repeatability of the *in situ* method was ~0.2 pixels or 0.9 μm r.m.s., enabling slope errors <0.1 μrad to be measured at 5–10 m from a mirror. The above methods can also

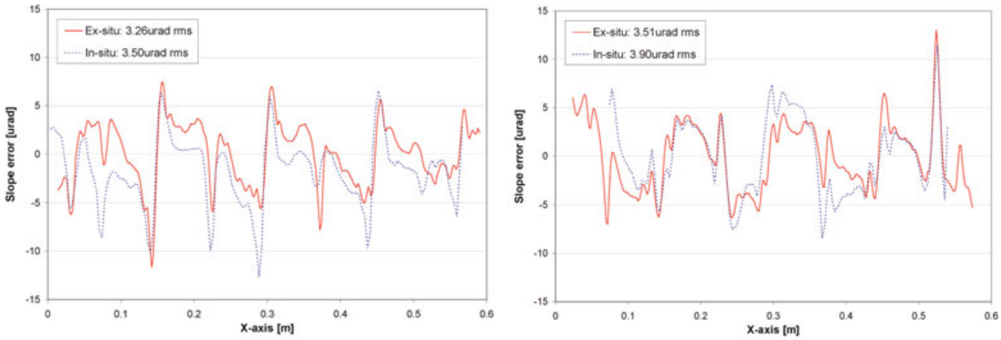

FIGURE 2. *Ex situ* and *in situ* slope errors at beamlines I02 (left) and I04 (right).

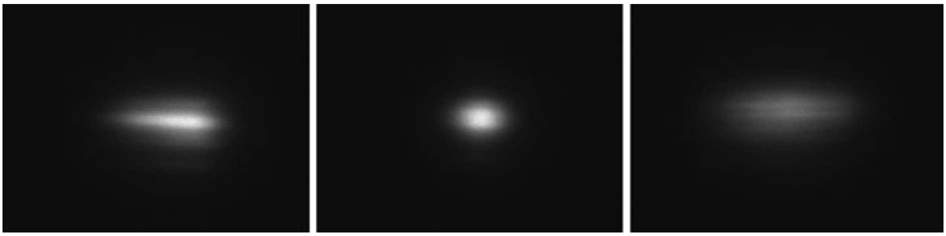

FIGURE 3. *In situ* beam improvements at beamline I19: initial (left), focused (centre), deliberately defocused (right). All images have a field of view ∼595 × ∼446 μm.

inspect and optimize mechanically bent mirrors. Good agreement between the different methods gives confidence in their validity.

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